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Decarbonizing Sweden's energy and transportation system by 2050

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ABSTRACT

Decarbonizing Sweden's transportation sector is necessary to realize its long-term vision of eliminating net greenhouse gas (GHG) emissions from the energy system by 2050. Within this context, this study develops two scenarios for the transportation sector: one with high electrification (EVS) and the other with high biofuel and biomethane utilization (BIOS). The energy system model STREAM is utilized to compute the socioeconomic system cost and simulate an integrated transportation, electricity, gas, fuel refinery, and heat system. The results show that electrifying a high share of Sweden's road transportation yields the least systems cost. However, in the least-cost scenario (EVS), bioenergy resources account for 57% of the final energy use in the transportation sector. Further, a sensitivity analysis shows that the costs of different types of cars are the most sensitive parameters in the comparative analysis of the scenarios.

Keywords:

Energy system modeling;
Transportation;
Electric transportation;
Biofuels and biomethane;
STREAM model;

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1. Introduction

The transportation sector has received increased attention over the past decades owing to the high dependency on fossil fuels and greenhouse gases (GHG) [1, 2]. As a result, several agreements, both national and international, have been prompted with an aim to reduce the environmental GHG footprint from both the transportation sector and the energy system as a whole [3–5].

The European Union has prioritized the decarbonization of the energy system by setting the long-term targets of reducing GHG emissions by 20% by 2020 and 80–95% by 2050 [3]. More specific targets include ensuring that renewable energy sources account for at least 10% of the energy used in the transportation sector by 2020 [4]. Under the international agreement, each country has individual targets [6]. The Nordic countries are pioneering the implementation of a clean energy policy, and Sweden is one of the leading EU member countries in terms of low-carbon intensity and increased share of renewable energy sources in the energy system [7].

While Sweden's electricity and district heating generation portfolio mainly relies on carbon-neutral technologies, whose primary supply resources are nuclear energy, hydropower, and bioenergy, the transportation sector highly depends on fossil fuels. In 2014, the transportation sector accounted for about 45% of GHG emissions in Sweden's energy system [8]. Therefore, to meet the ambitious long-term vision of zero net GHG emissions by 2050, radical restructuring of fuel use and vehicle stock is warranted. As a result, the Swedish government has proposed an ambitious medium-term target of developing a vehicle fleet that is independent of fossil fuels by 2030 [5].

The Swedish energy system is expected to be dramatically transformed into a system with stronger couplings and interactions between energy sectors. Thus, adopting a holistic system perspective is needed to

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assess various transportation scenarios [9]. The Swedish energy system is headed toward a zero net GHG emissions, rendering the integration of energy sectors increasingly important [10–12]. Energy production from an increased share of variable renewable energy (VRE) sources - for example, wind, which is characterized by a variable, as well as uncertain and location-specific power generation - can be efficiently facilitated using various flexible resources along with energy system integration. Flexible generation units, storage facilities, interconnectors, and demand-side management are flexible resources needed to cost-efficiently and effectively integrate higher VRE penetrations in the future [13, 14]. The future transportation sector will enable stronger couplings between energy sectors and thereby, make the energy system more flexible; for example, electric vehicles (EVs) can provide demand-side flexibility in terms of charging from the grid (grid-to-vehicle [G2V]). The potential benefit of the transportation sector substantially relying on bioenergy is the excess heat production from biorefineries [7]. Combining a carbon source from, for example, biomass, with hydrogen from an electrolyzer to produce bioelectrofuels is one way of integrating the power, heating, gas, and transportation systems and can render a power system more flexible [15–17].

Studies have demonstrated the potential flexibility benefits of integrating higher shares of EVs in the energy and transportation system. Kempton and Tomic [18] explained the concept of V2G and the potential benefits of implementing V2G in the energy system. Kiviluoma and Meibom [19] investigated the influence of power system investments when integrating a higher penetration of wind power along with EVs, and heat storages. They showed that EVs enable the temporary storage of electricity for later use and thus, increase the flexibility of the power system. Juul et al. [20] explored strategies for charging EVs in the electricity market. EVs can add demand-side flexibility. To this effect, Tveten et al. [21] examined market effects on VRE integration with increased demand-side flexibility. Using a linear optimization model, Juul and Meibom [22] discussed the optimal configuration of an integrated power and transportation system. Skytte et al. [23] and Skytte and Bramstoft [24] employed the energy system model, sustainable technology research and energy analysis model (STREAM), to compute and compare future transportation scenarios including high shares of electricity, hydrogen, and biofuels.

Decarbonizing the transportation sector requires the higher utilization of bioenergy resources [25–39]. Börjesson et al. [25] conducted a comprehensive review of the future use of biofuels in the transportation sector using energy–economic modeling and included both national and international studies on the energy and transportation sector. The review revealed significant variations in the projected market shares of biofuels in future transportation scenarios. However, Börjesson et al. conclude that biofuels play a key role in the medium term, while electricity is more favorable in the long run. Börjesson et al. [26] and Grahn et al. [27] documented the technical, economic, and potential benefits for future biofuels on the basis of studies performing life-cycle assessments, and Grahn and Hansson [28] presented prospects for biofuel utilization in the Swedish transportation sector by 2030 using data on current and future production plants. Their study highlights Sweden's plans and demonstration projects as well as the utilization of fuels such as ethanol, methanol, dimethyl ether (DME), methane, and biodiesel. Börjesson et al. [29] conducted a modeling analysis of biofuels in Sweden's road transportation. Adopting a bottom-up optimization model for the Swedish energy system, they investigated the cost-efficient utilization of biofuels and found that methanol and biomethane are preferred fuels for the future. Furthermore, they showed that the use of second-generation biofuel along with plug-in hybrids in the transportation sector could play a prominent role in achieving medium-term Swedish climate targets. Börjesson et al. [30] found high utilization of methanol, biomethane, and electricity in the Swedish road transportation and Börjesson et al. [31] suggested that high methanol utilization led to the most cost-effective, alternative transportation fuel pathway for Swedish passenger cars. Focusing on Sweden's bus fleet, Xylia et al. [32] showed that the share of renewables in the public bus fleet was about 60% in 2014, with biodiesel and biogas as preferred fuels; however, they concluded that electric buses are a promising future technology.

The literature overview indicates that the transition of the transportation sector has received broad attention in recent years. However, there remains a research gap in terms of holistic energy system analyses, which assess integrated energy and transportation systems. Thus, there is a need for, more analyses on the socio-economic potentials for the cross-sectoral integration of the transportation sector. In particular, an investigation of the future role of fuels such as biomass-to-liquid (BTL), gas-to-liquids (GTL), electricity, and renewable gas, in the transportation sector is crucial.

This study makes the following contributions to the research field. It adopts a holistic energy system perspective to investigate the transportation sector as an integrated part of the energy system, which could facilitate future interrelations between energy sectors. The analysis focuses on the future role of EVs and biofuels and renewable gases in Sweden's transportation sector. The energy system model, STREAM, computes the socioeconomic value of the overall system cost and simulates the system integration of the transportation sector with the electricity and heating sectors with an hourly temporal resolution. This study develops two scenarios for the decarbonized Swedish transportation sector in 2050. The first scenario (EVS) includes a high percentage of electric transportation in the light transportation segment and the second scenario (BIOS) involves a high percentage of biofuel use in the transportation sector. The Nordic Energy Technology Perspective (NETP) 2013 [2] is used to represent the Swedish energy supply mix. This NETP 2013 offers a potential carbon-neutral scenario (CNS) that illustrates a pathway to an almost carbon-neutral Nordic energy system by 2050 while accounting for future developments in surrounding Nordic countries. CNS is also a reference scenario for the transportation sector in this analysis, thus allowing a comparative evaluation of two developed transportation scenarios, that is, electric vehicles scenario (EVS) and bioenergy scenario (BIOS).

The remainder of this paper is organized as follows. Section 2 describes the energy system model used to conduct simulations of scenarios along with the main data assumptions. Section 3 describes the power, heat, and transportation sectors in the 2050 scenarios. Section 4 present the model simulation results and evaluates sensitivities regarding the main assumptions. Section 5 concludes with findings.

2. STREAM model

In this study, the energy system simulation tool, STREAM, is used to conduct simulations of future Swedish energy and transportation scenarios. STREAM is a bottom-up energy system model that enables scenario analyses of an integrated power, heating, gas, fuel refinery, and transportation system (Figure 1). By

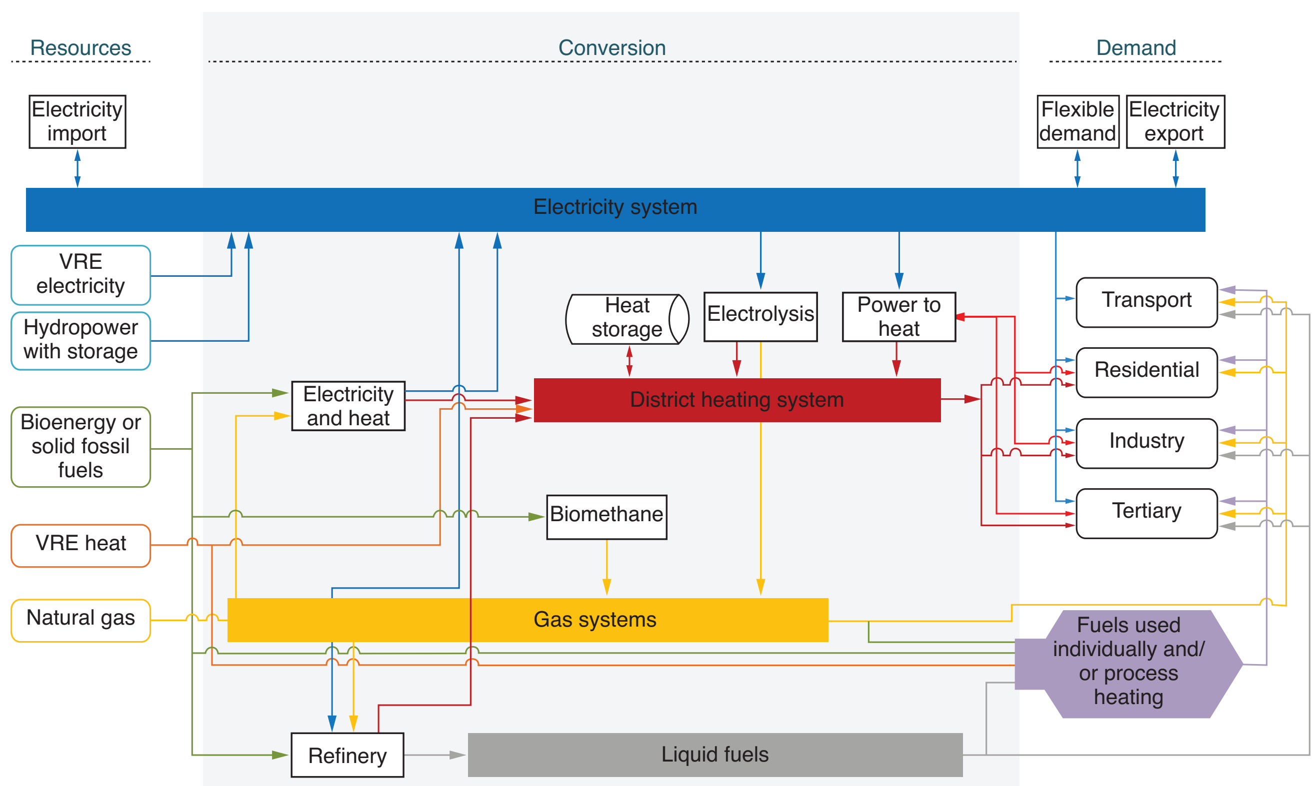

Figure 1: Integrated energy system modeled in STREAM

satisfying energy demand, the model simulates energy flows across the entire energy system. Thus, STREAM is a tool suitable to simulate various energy and transportation scenarios and conduct comparative analyses of respective solutions [40, 41].

The STREAM model comprises two sub-models: the flow model and the duration curve model:

The flow model accounts for the annual energy balance between demand and supply. It simulates couplings and interactions between the power, heating, gas, fuel refinery, and transportation systems. Using metrics for economic growth, the model determines projections of energy demands and computes the final energy consumption. The results include socioeconomic costs, GHG emissions, energy resources, and fuel conversion.

The duration curve model computes the energy balance between demand and supply on an hourly temporal resolution. It computes the optimal operation of the energy system by prioritizing VRE vs. dispatchable electricity generation, combined heat and power vs. district heat boiler generation, and optimal utilization of storage facilities. In addition, it allows for varying amounts of flexible and non-flexible demand. By performing a systematic iterative process, the results obtained in the duration curve model are subsequently used as input parameters in the flow model.

Both sub-models in STREAM are utilized to obtain a solution that optimizes the annual operation of the energy system on an hourly basis [42]. STREAM simulates the energy system in an island mode in which electricity trades with adjacent markets on an hourly time scale only appears to balance the power system. Furthermore, STREAM enables the modeling of flexible electricity demand. The following flexibility options are modeled on the basis of user-defined settings: 1) charging of electric vehicles (flexible or night charging), 2) demand-side flexibility (shift in electricity demand from peak to base), and 3) flexible production of electrofuels (e.g., hydrogen). Flexible demand is modeled with the objective of minimizing residual peak demand and thus, limiting dispatchable power capacity or power transmission capacity.

This study focuses on transportation as an integrated part of the energy system. Figure 2 illustrates the conceptual modeling approach for the transportation system in STREAM.

In STREAM, the transportation system consists of two independent sub-sectors, passenger and freight. The transportation work in the reference year is specified according to statistical data. To estimate future transportation work, STREAM uses metrics for economic growth along with specific energy intensity factors, which vary between the transportation sub-sectors. This modeling approach ensures that all simulated scenarios satisfy the same level of transportation work; however, the fuel used in each transportation scenario may vary by vehicle efficiency.

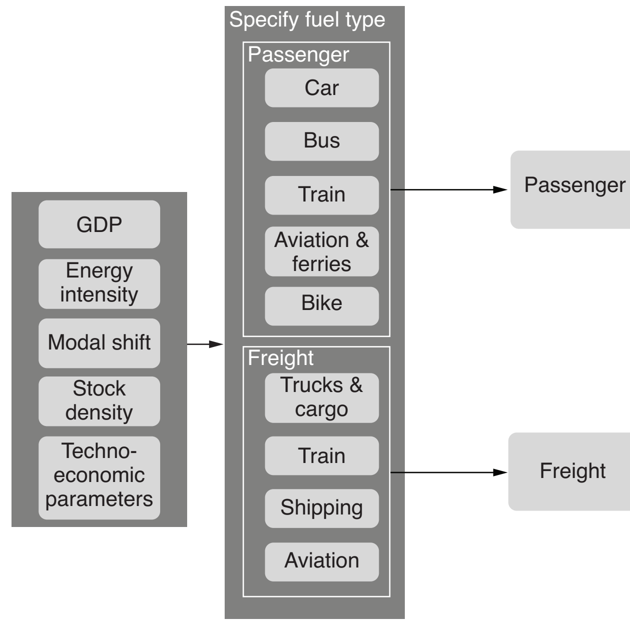

Figure 2: Conceptual model for transportation system in STREAM

To facilitate a more detailed modeling of the transportation system in STREAM, transportation work is specified in further detail: 1) specification of vehicle types used in Sweden, for example, car, bus, train, plane, or bike; 2) utilization degree referring to stocking density; 3) scenario-specific composition of fuels, for example, electricity or biofuels, used for transportation of both passenger and freight.

The STREAM modeling framework enables the computations of associated costs and emissions related to total fuel consumption in the entire energy system. Moreover, using an hourly time resolution, STREAM allows the modeling of variable power production from, for example VRE, as well as flexible charging of EVs.

2.1. Main data assumptions

In this study, the reference scenario is the normative carbon-neutral scenario (CNS) outlined in the NETP 2013 project [2]. It includes both international and national energy policy targets and thus, represents a scenario in which the aggregated emissions from the Nordics can be potentially reduced by 85% by 2050 compared to 1990 levels. NETP 2013 forms the data input for the future generation mix in the electricity, district heating, and process heating sector. The main data sources for power- and heat-generation technologies are from the technology data for energy plants catalog [43].

In terms of the transportation sector, the 2050 projections for passenger and freight work are based on metrics extracted from CNS [2]. These projections are estimated using historical trends for economic growth and transportation work as well as assumptions for future transportation work, transportation demand, and efficiency improvements. In this way, transportation work for passengers and freights (passenger km and ton km) is satisfied; however, owing to varying vehicle efficiencies, the amount of fuel used in the transportation sector differs by future scenario. In the modeling framework, cargo vans and trucks are aggregated, although cargo vans account for 82% of vehicle activities and medium and heavy trucks constitute 7% and 11%.

In all the scenarios, EVs are charged as follows: 1) 40% EVs are assumed to charge whenever it is best for the system and 2) 40% EVs are assumed to charge their batteries during nighttime, that is, 23:00–6:00. In other words, a maximum 80% of EVs can be charged during nighttime, potentially creating new peak consumption hours and indicating a shift in consumption from daytime to the nighttime.

Fuel and CO_2 prices

Fuel and CO_2 prices can significantly influence the results. Table 1 presents the price levels of fossil fuels, biofuels, and CO_2 emissions by 2050. The price estimates by 2050 for fossil fuels, that is, hard coal, oil, and natural gas, are adopted from NETP 2013 [2]. Bioenergy price projections are estimated using the global assessment model (GCAM) [44]. CO_2 price reflects the marginal abatement costs in the electricity system and shows a substantial increment toward 2050, which is encouraged by the ambitious energy targets [2].

Table 1: Fuel and CO_2 prices by 2050

Fuel prices		
Natural Gas	6.02	€/GJ
Nuclear – Uranium	4.00	€/GJ
Biomass (Straw, wood waste)	9.10	€/GJ
Biomass (Energy crops)	9.78	€/GJ
Biomass (manure)	0.00	€/GJ
Coal	1.58	€/GJ
Oil	16.40	€/GJ
CO_2 price	120.30	€/t CO_2

Production of fuels

This study considers various types of fuels used in the transportation sector. The model includes fossil fuels such as gasoline, diesel, and natural gas since these fuels are heavily used in Sweden's current transportation sector. The transition toward a decarbonized transportation sector warrants fuels produced from renewable energy sources. Thus, the model considers several biofuels, renewable gases, electrofuel, and electricity for transportation.

The category of biofuels includes biodiesel, methanol, ethanol, and bio-jet fuels. Bioenergy resources can be converted into fuels by utilizing biomass-to-liquid (BTL) technologies. Bioethanol is produced using fermentation technologies, where 1 g bioethanol is produced from energy crops such as corn, while 2 g bioethanol is made from lignocellulosic biomass, for example, straw. In this study, methanol and DME are modeled as one fuel since the energy balance is similar when considering both production process and vehicle efficiency [17, 36, 45, 46]; however, the cost of producing DME might be higher [45]. Methanol or DME is synthesized using a bioenergy resource, where biomass gasification converts biomass into syngas and thereafter, from syngas to methanol through a catalytic synthesis process. Thus, gas-to-liquid (GTL) fuels are an integrated part of the BTL conversion. In this study, electrofuels have properties of methanol or DME, but are produced through biomass hydrogenation, where the carbon source is combined with hydrogen. This is an effective way to produce more transportation fuel using the same available biomass resources, and furthermore, increase the system integration of the power, gas, heating, and transportation system. Second-generation biodiesel is produced from straw or wood using biomass gasification and Fisher–Tropsch (FT) synthesis. Bio-jet fuel is kerosene produced from straw using a BTL technology, where the production process includes the gasification of biomass and FT synthesis, among others. Renewable gasses include upgraded biogas produced from anaerobe digestion, SNG from biomass gasification, and hydrogen produced from electrolysis.

The costs of biofuel production technologies and energy balances implemented in STREAM are presented in Table 2.

3. Description of 2050 scenarios

3.1. Power and heating sectors

The composition of the power and heating sectors obtained in the CNS are used as exogenous input parameters in all scenarios with certain adjustments:

The future mix for the Swedish power sector has been widely discussed, and in particular, the role of nuclear power remains uncertain given the vision of phasing-out nuclear energy [2, 5, 7, 49]. Currently, nuclear power plays a significant role and constitutes approximately 42% of the total power generation and 53% of Sweden's electricity demand [50]. Thus, the future prospects of nuclear power influence Sweden as well as the surrounding countries' generation mix. While NETP 2013 [2] still considers nuclear power as a supply option, NETP 2016 [7] promotes the phasing out of nuclear energy by 2050 and presents a sensitivity analysis on a fast phase-out in Sweden. According to NETP 2013, Sweden will be a major electricity exporter by 2050, exporting 143 PJ, while in NETP 2016, electricity supply and demand appears to balance out. The phase-out of nuclear power in NETP 2016 is facilitated by the increased capacity of low-cost onshore wind technologies and reduced net export of electricity. Moreover, Sweden's nuclear power capacity is intended to be decommissioned by 2050 [51]. By excluding nuclear power generation from NETP 2013 CNS, a composition of an electricity mix similar to that in NETP 2016 can be found. This study adopts this composition of electricity mix.

The electricity generation mix is implemented in STREAM with emphasis on consistencies in the final electricity generation for all three future scenarios. However, because the electricity demand varies by future scenario, generation from onshore wind turbines is increased or decreased to meet demand.

STREAM covers energy services in the residential, tertiary, and industrial sector. Furthermore, STREAM computes endogenous demand from a district heat boiler. Energy demands in the residential, tertiary, and industrial sector are satisfied by implementing an identical percentage allocation of supply configuration as in CNS.

The design of the transportation sector is implemented in STREAM according to the purpose of the specific scenario, that is, CNS, EVS or BIOS.

Table 2: Fuel production-costs and energy balances used in STREAM

Fuel production	Feedstock	Energy balance: inputs per unit of fuel output			Investment Cost [€/GJ/y]	O&M costs [€/GJ/y]	Distribution costs[5] [€/GJ]
		Biomass (in)	Electricity (net in)	Heat (net in)			
1.g. Bioethanol[1]	Energy crops	1.72	0.03	0.38	18.6	2.05	3.9
2.g. Bioethanol[1]	Straw	2.44	–0.07	–0.60	69.0	5.3	3.9
2.g. Biodiesel[1a]	Straw/wood	1.79	–0.05	–0.38	112.9	3.4	3.1
Biomethane – Biogas[2]	Manure etc.	2.5			64.8	2.0	7.8
Biomethane – SNG[1]	Wood	1.59	0.14	–0.25	118.0	3.5	7.8
Methanol/ DME[1]	Wood	1.89		–0.67	35.1	1.1	4.2
Electrofuel – methanol/ DME[3]	Wood	0.75	0.53	0.10			4.2
Bio-jet[4b]	Straw	2.08	–0.02	–0.44	176.8	5.3	3.1
Hydrogen[1]			1.47	–0.26	55.6	2.3	7.8

Technology data are taken from several sources [1][45]; [2][47]; [3][15, 16]; [4][48]; [5][29].

Production of certain fuels has bi-products such as, gasoline, diesel, and naphtha, which subsequently can be used in other transport means. The modeling approach applied in this study summarize the fuel output, however, the different end products are noted by the superscript later.

[a] gasoline is produced as a by-product. The ratio between biodiesel and bio gasoline production is 2.3.

[b] gasoline and naphtha are produced as by-products. An equal amount of bio gasoline and bio jet kerosene is produced. 2.67 units of bio jet kerosene are produced compared to naphtha.

3.2. Transportation systems

Current Swedish transportation sector

The Swedish transportation sector highly depends on oil-based fossil fuels, that is, diesel and gasoline. Diesel and gasoline account for approximately 85% of the final domestic consumption in the transportation sector, and the fuel mix in the sector is homogeneous. However, the share of biofuels in the transportation sector is rapidly increasing and accounts for approximately 10% of the final energy use in the domestic transportation sector [50, 52].

Future transportation scenarios

A literature overview of the transportation scenarios by 2050 is conducted to elucidate pathways that have shown promising results in previous studies. The overview includes both Swedish [2, 28–31, 33] and Danish [2, 34–39] studies, where each of the studies may assess more scenarios. While Swedish studies present more aggregated results, for example, the road transportation sector, Danish ones tend to distinguish between different types of transportation. The studies adopt simulation [34–39] and optimization [2, 29–31] models. Furthermore, some studies do not include methanol/DME [2, 34, 35, 39]. The overview clarifies general trends in transportation scenario pathways, and the learnings are used to design transportation scenarios investigated in this study.

There is a strong expectation from the roll out of EVs in the literature. Pathways for the car sector show that electric vehicles have a share of 60–95% in most scenarios. Some studies suggest that the remaining proportion in the car vehicle fleet is accounted for by methanol or DME (10–85%) [29–31, 33, 36–38], biodiesel (up to 40%) [2, 34, 35, 39], bioethanol (25–50%) [2, 35], and renewable gas (up to 15%) [29, 30, 33, 34].

Scenarios for the bus fleet show different pathways with a high utilization of electricity, methanol or DME, biodiesel, and renewable gas. The highest electrification of the bus fleet is estimated to be 50–75% [34, 35], while lower shares 10-25% are estimated in [36–38]. Methanol or DME account for 60–90% [31, 36, 38] and biodiesel ranges from 67% to 75% [2, 35] and was even reported to be at 25% [34]. Renewable gas is between 30% and 50% [2, 31, 34, 35]. The illustration for the bus fleet fuel composition is similar to that for vans in the freight transportation category.

The literature included in this study suggests that electric trucks will not offer promising results by 2050 given their use of high energy-content fuels. A similar scenario is derived for sea transportation. Some studies consider methanol or DME to be used in both categories [31, 36, 38], while other suggest the use of biodiesel [2, 34, 35]. Renewable gas are also recognized with high shares in trucks (up to 75% [34], about 50% in [35], and 36% in [2]) but with lower shares in sea transportation (15–20%) [2, 35].

The literature review suggests three main pathways toward a decarbonized transportation sector: 1) biodiesel/renewable gas, 2) electrification of light duty vehicles, and 3) methanol/DME/renewable gas. Thus, this study explores three scenarios in the context of the transportation sector: 1) CNS (with high utilization of biodiesel); 2) EVS (high electrification of the light transportation segment, while biofuels are used for heavy transportation), and 3) BIOS (high utilization of methanol/DME/renewable gas).

The transportation categories in CNS change the fuel mix from fossil to a much higher share of electricity, hydrogen, and biofuels. Within the biofuels, biodiesel is used as the main substitute for traditional diesel.

In EVS, a high share of the transportation sector is electrified. This scenario pushes the limit of the highest shares of e-mobility in the literature. Here, the entire car fleet as well as transportation by trains is electricity based. The future bus sector, cargo vans, and short-to-medium distance trucks sectors will primarily run on electricity, whereas the remaining fuel used is biofuels, that is, mainly methanol/DME and biomethane. The aviation sector is uses bio-jet as fuel.

In BIOS, biofuel-based transportation can accelerate the path to a decarbonized transportation sector. Only trains are electrified in this scenario, while the remaining transportation demand is met by biofuels, with methanol/DME and biomethane as preferred fuel choices. The design of fuel composition is inspired by findings from the literature overview.

The three future transportation scenarios vary by fuel mix composition. Figure 3 presents the fuel mix in the transportation sector by 2050 for the three scenarios.

4. Results

4.1. Simulated energy systems

The present production of power and district heating in Sweden is almost carbon-neutral. Since the transformation toward a carbon-neutral transportation sector depends on the overall energy system configuration, the electricity and

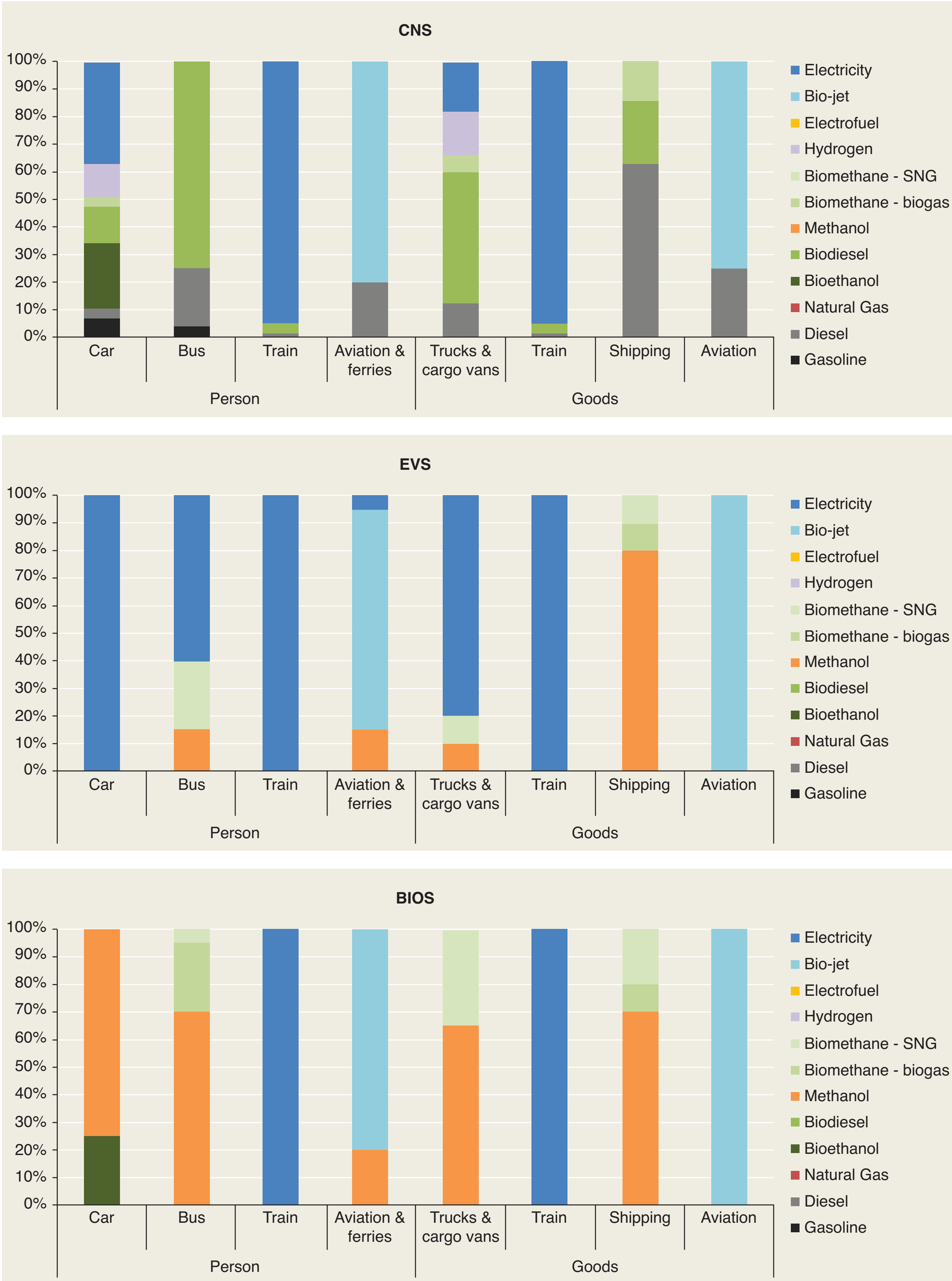

Figure 3: Fuel use in transportation sector in CNS, EVS, and BIOS by 2050 (measured as fuel consumption in percent person transportation work (pkm) or percent freight transportation work (tkm))

district heating systems are designed in consistency with the description in Section 3. Figure 4 illustrates the configuration of the future electricity portfolio. An underlying assumption for the future scenarios is that the total annual national electricity generation equals the annual national electricity demand. In this way, the annual imported electricity equals the annual exported electricity. However, interconnectors to adjacent markets allow electricity trades on an hourly basis.

In the base year (2010), the Swedish electricity sector is primarily supplied by hydro- and nuclear power, which accounts for 46% and 40% of the total electricity generation. Biomass plants, wind turbines, coal plants, and gas turbines account for the remaining electricity production.

According to CNS, in the future Swedish power system, nuclear power generation is phased-out and the major suppliers of electricity by 2050 will be hydropower and wind power. Hydropower generation in 2050 will account for 41% of the total electricity production, which corresponds to an electricity production of 70 TWh. The share of wind power in CNS increases to 44% by 2050 corresponding to a production of 75 TWh.

Figure 4 illustrates how the generation from wind is adjusted to meet the annual Swedish electricity demand. High electrification of the energy system is key in EVS, where a high share of electric transportation enters the market. Consequently, this energy system requires 5% higher electricity demand compared to CNS. The higher electricity demand is met by increasing the generation from onshore wind power by 9 TWh, leading to a total wind generation of 84 TWh in EVS by 2050. In BIOS, the electricity demand is lower. Thus, onshore wind generation is reduced accordingly, yielding a reduction in onshore wind generation by 13 TWh compared to CNS.

In this scenario, the energy sectors in the future Swedish energy system are more integrated. The district heating system is integrated with both the electricity system, through heat production from co-generation plants (CHP) and heat pumps, and the transportation system, for example, through excess heat from biorefinery processes. Furthermore, district heat boilers can be a part of the future district heating system as backup capacity, particularly in periods when heat production from other sources was insufficient to meet the district heating demand [53]. Figure 5 presents the district heating production and demand in the base year and future scenarios.

Heat generation from co-generation plants is determined in the CNS from NETP, wherein a large proportion of the district heat production stems from co-generation plants that either use biomass or municipal waste resources.

Heat pumps are introduced and allow efficient heat generation and increase power system flexibility. The highest utilization of heat pumps is introduced in EVS and CNS, where 31 PJ and 20 PJ heat is produced.

Since most of the heat production is predefined, the significant potential for cost-effective utilization of excess heat from biorefineries cannot be efficiently used

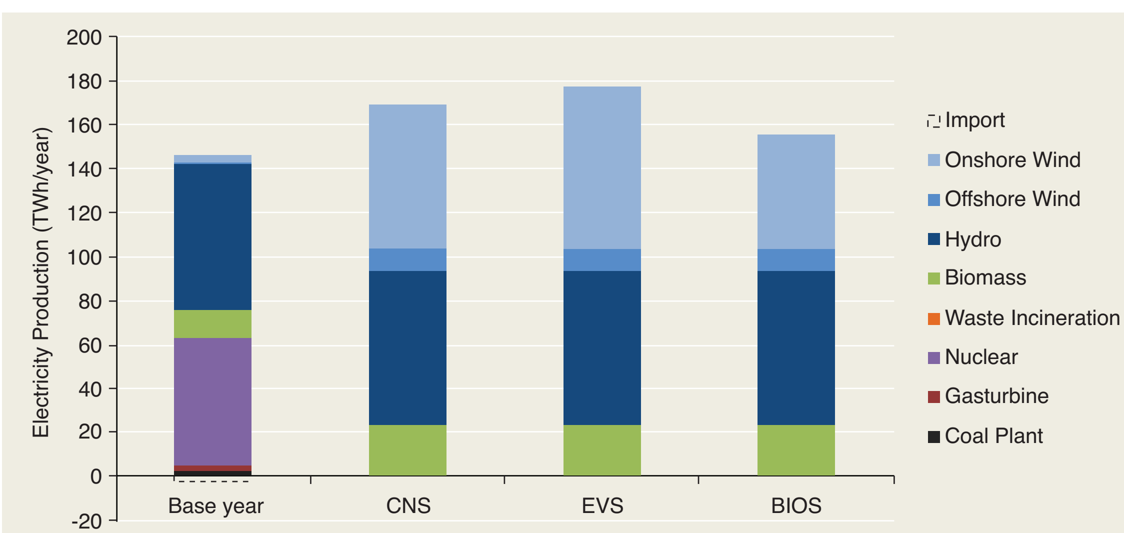

Figure 4: Electricity generation portfolio in three 2050 scenarios compared to base year

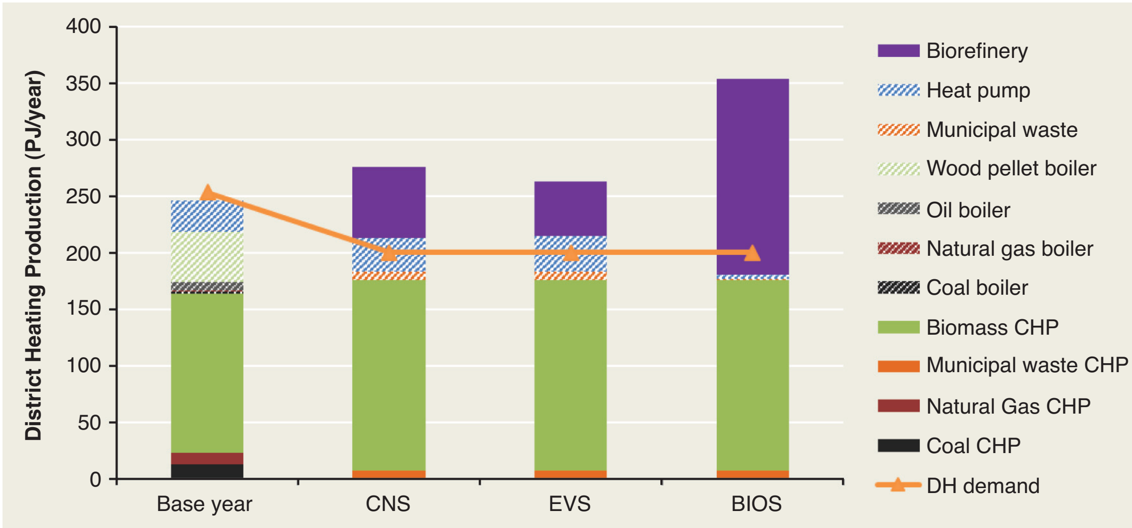

Figure 5: Technology mix in district heating sector in base year and three 2050 scenarios

in the energy system. Relying on the assumption that biorefineries are connected to the local district heating system, excess heat production from the biorefinery processes can be utilized to replace traditional district heating supply technologies. The amount of excess heat from biorefineries varies by scenario and is related to the fuel use in the transportation system. The highest rate of excess heat production appears in BIOS with a value of 174 PJ, followed by CNS and EVS with 63 PJ and 48 PJ. The potential utilization of excess heat might be overestimated owing to the aggregated spatial resolution, which allows all refineries to be connected to a district heating grid that supplies to the total Swedish district heating demand. However, irrespective of scenario, the cost-efficient utilization of excess heat should be further investigated with a higher spatial resolution and information on local district heating grids [54–56].

In all the scenarios, heat production exceeds district heating demand. This indicates that overproduction of heat is cooled down. These periods appear, for example, when biomass co-generation plants are required to produce electricity and because of the fixed heat–power ratio in back-pressure plants the plants also produces heat.

4.2. Simulated transportation systems

Actual fuel consumption in the transportation sector is computed in STREAM following the modeling approach (Figure 2) and the defined transportation scenarios (Figure 3). The Sankey diagrams in Figure 6 illustrate fuel use in the transportation sector for the three investigated scenarios divided by transportation type and indicating transportation of passengers or goods.

In CNS, the transition from fossil fuels toward a low-carbon transportation sector is achieved by using 62% biofuels, 9% electricity, and 6% hydrogen. Among the biofuels, biodiesel accounts for 28% of total fuel use in the Swedish transportation sector by 2050. In CNS, fossil fuels continue to be used in the transportation sector and account for 22% of the total transportation energy use.

In EVS, electricity accounts for 43% of the total fuel use. In particular, the light and medium road transportation segment as well as rail transportation is electrified in this scenario. Since the transportation sector in EVS is decarbonized, 57% of fuel used in the transportation sector stems from bioenergy resources. This indicates the key role of bioenergy resources in a future electrified transportation system. It is noteworthy that the energy use for car passenger transportation is lower in EVS than in CNS and BIOS because electric motors have higher efficiency than motors using fuels.

BIOS is characterized by a high utilization of bioenergy resources in the transportation system and describes a potential future scenario in which bioenergy fuels account for almost 100% of the total fuel use in the transportation sector. Methanol or DME accounts for 68%, while bioethanol is 12%. Renewable gases enter the transportation system and account for 5% primarily because of its utilization in heavy and long-distance transportation.

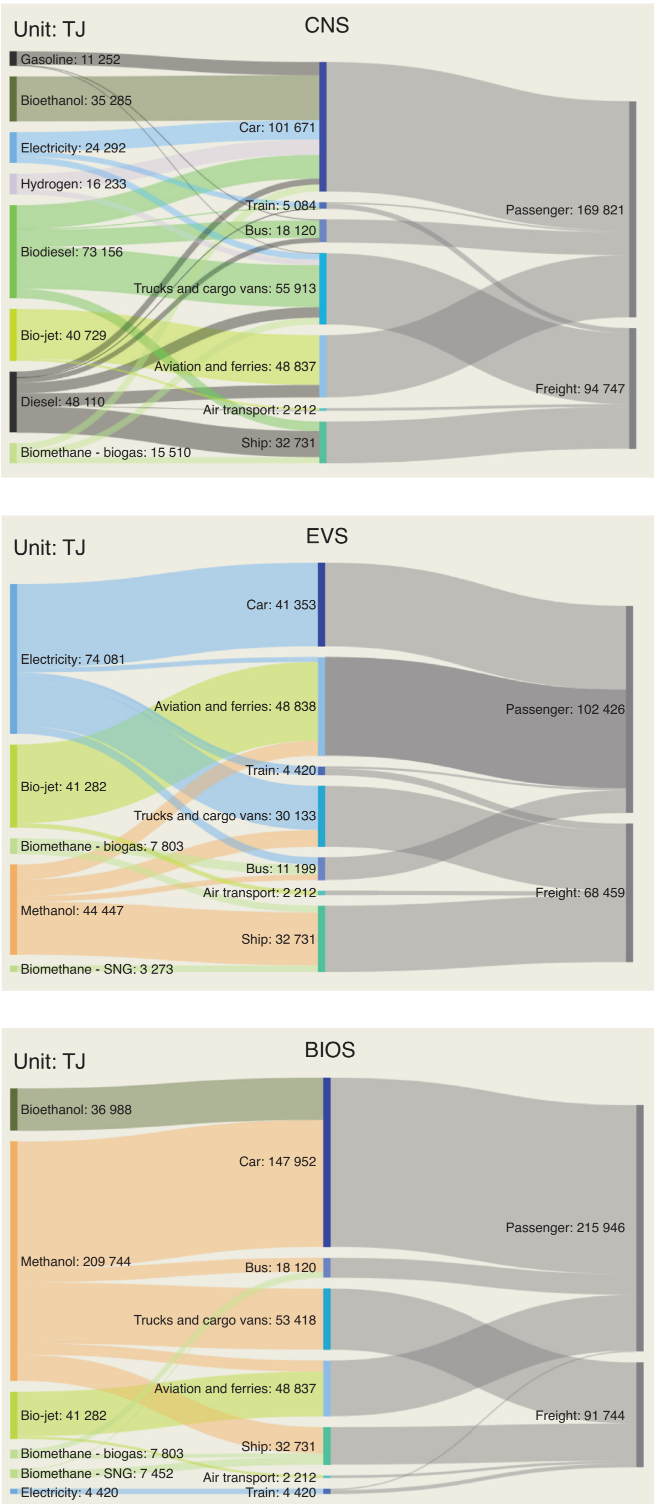

Figure 6: Sankey diagram for fuel use in transportation sector for CNS, EVS, and BIOS by 2050

4.3. Energy used and available resources

Resource management is increasingly important in the transition toward a cost-efficient and sustainable future energy system. In integrated energy systems, primary resources are converted into various energy services. Thus, it is important to investigate the energy chain from primary resources to downstream energy services. By applying STREAM, the national Swedish energy resources can be compared with actual resources used in the three future scenarios and accordingly, evaluated in terms of self-sufficiency.

Bioenergy resources can be used for various proposes in several energy sectors. In this study, bioenergy resources are assumed to be carbon neutral. Thus, bioenergy resources will play a prominent role in Sweden's future energy system, which meets the long-term vision of zero net GHG emissions. Expectations of higher bioenergy utilization are met in CNS, in which by 2050, Sweden will be importing biomass resources, straw and wood waste.

In this study, importing bioenergy resources is allowed in the modeling framework. The national Swedish techno-economical available resources estimated in CNS are used to facilitate the resource utilization assessment.

Figure 7 compares the techno-economic potentials with the actual resources use both in the base and the three future 2050 scenario: CNS, EVS, and BIOS.

Figure 7 presents the transition from the current fossil fuel-based energy system to a future fossil-independent energy system. This transition is facilitated by an increase in wind power and the utilization of bioenergy resources, while the use of fossil fuel is significantly reduced.

In CNS, Sweden is a net importer of biomass (i.e., straw and wood waste) and to a small extent, certain fossil fuels continue to be used in, for example, the transportation, industrial, and tertiary sector, by 2050. Even though the EVS suggests high electrification of the transportation sector, Sweden will still import biomass resources. BIOS is evidently the scenario with the highest utilization of bioenergy resources.

In this study, bioenergy resources are used in all energy sectors, with the highest utilization in the transportation sector, power and heating sector, and industrial sector.

According to current knowledge, certain segments of the transportation sector, that is, aviation, sea transportation, and long-haul trucks, seem difficult to electrify. The present study does not include electric highways; however, this technology might be a game changer in the future. In other words, energy-dense fuels are needed, which in this study, are produced on the basis of biomasses. The transportation sector accounts

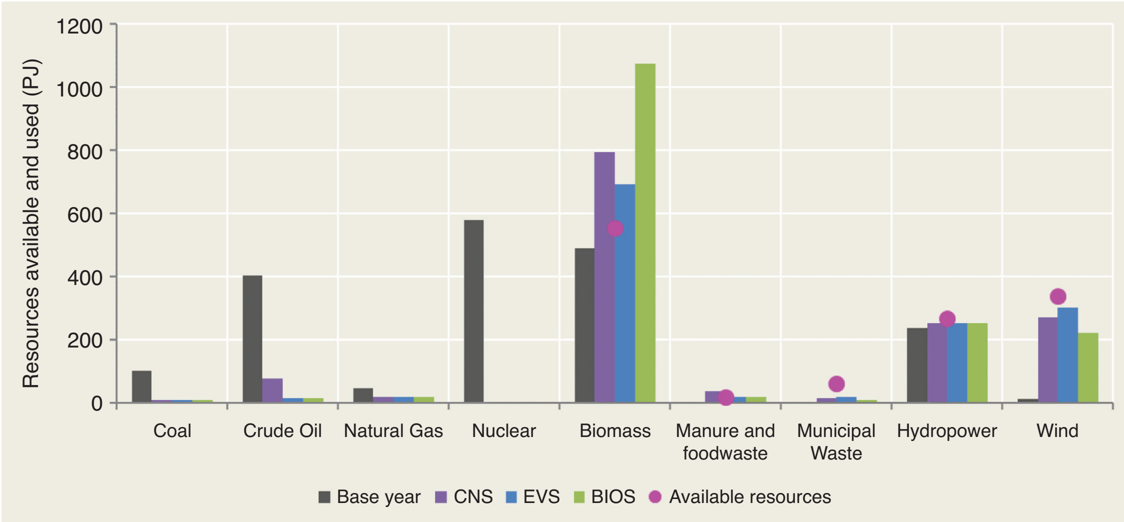

Figure 7: Comparative analysis of available national resources and actual resource use in base year and three 2050 scenarios

for 315 PJ in CNS, 195 PJ in EVS, and 575 PJ in BIOS; this should be compared to the 555 PJ national available biomass resources. This suggests that the Swedish transportation sector can be decarbonized in CNS and EVS while still leaving room for bioenergy utilization in other sectors.

The design of the industrial sector is identical in all scenarios and thus, yields identical bioenergy consumption, namely 204 PJ. In addition, the power and district heating system is designed to consume the same amount of bioenergy in all scenarios, that is, 275 PJ, which accounts for 50% of the national biomass potential. This energy system configuration could be redesigned by reducing biomass utilization in back-pressure plants. The utilization of biomass for electricity production has been investigated in the literature [57]. Instead of importing biomass for electricity and heat production, cheap VRE technologies such as onshore wind could be installed to ensure sufficient electricity generation, the district heating system could be electrified using heat pumps, and the use of excess heat from biorefineries can be increased cost-efficiently. Some of these measures have also been implemented in the latest version of NETP [7].

Sweden is a country with high national biomass potential. Sustainable carbon will be a scarce resource in the future, and thus, biomass, should be used in sectors with no alternative option. Further, other countries may face a shortage in biomass in the future and Sweden could potentially become a net exporter of biomass or a country where biofuels are produced and distributed to other countries, thus efficiently using excess heat from refinery processes. Finally, the market price of bioenergy resources depends on global utilization; therefore, in case countries follows the scenario of over-utilization of biomass resources, the prices of biomass are likely to increase significantly.

4.4. Systems costs

Total annual system cost is used to evaluate the scenarios and is presented in Figure 8. To identify elements causing the largest cost differences, total annual cost is disaggregated into the following five elements: investment in energy efficiency, capital cost, O&M cost, fuel cost, and CO_2 cost.

The result from the STREAM simulation shows that the total annual system cost in CNS is about €48.1 billion and in EVS, it is approximately €43.8 billion. Using CNS as a reference, the value corresponds to a reduction of 9.1%. The STREAM simulation finds BIOS to be the most expensive with a value of €48.2 billion, thus corresponding to an increment of 0.2% compared to CNS. These findings are in line with the results in Börjesson et al. [25], who reviewed studies investigating future transportation scenarios and found that electricity may be the most preferred fuel, at least for light transportation, in the longer term. Moreover, electrifying light transportation is shown as a cost-effective solution [33–35, 37–39].

Figure 9 illustrates a comparative assessment of the system costs in the future scenarios.

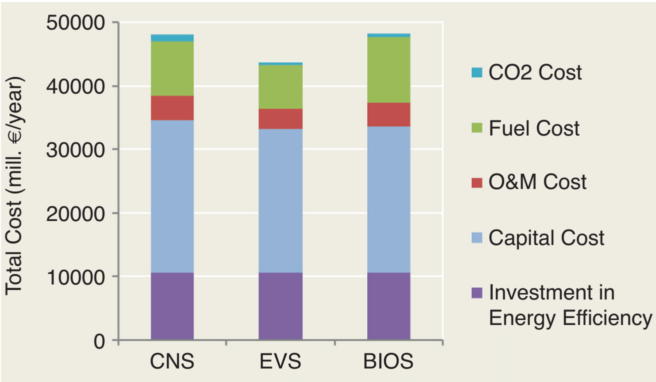

Figure 8: Total annual system cost in three scenarios by 2050

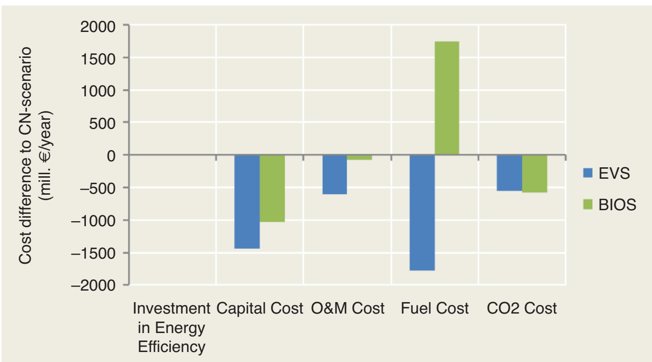

Figure 9: Cost difference in total annual system cost by 2050 between two alternative transportation scenarios and CNS

This section identifies and further discusses the key factors driving discrepancies in each of cost parameter. Figure 9 shows that EVS is the most cost-effective for the future scenarios. The total capital costs are about €1.4 billion lower in EVS compared to those in CNS. The main driver for this reduction is the capital cost of transportation and fuel refineries, which are €1.6 billion lower in EVS than in CNS. The electrification of the transportation sector lowers the utilization of fuels for transportation. Thus, a substantial reduction of 200% is achieved for fuel costs in the fuel refinery processes in EVS compared to CNS. This implies a significant reduction in total fuel costs, even though higher fuel cost is computed for district heat production technologies.

In EVS, the electrification of the transportation systems leads to higher demands for electricity. Thus, increased generation capacity is needed to meet the growing electricity demand. As mentioned, the share of onshore wind increases according to the rise in electricity demand, yielding a higher capital cost. Higher deployment of wind in EVS increases the need for flexibility in the power system. Electric vehicles can provide flexibility to the system; however, in EVS, the required capacity of interconnectors is 20.3 GW, as opposed to the current 10.7 GW [7], 17.2 GW in CNS, and 12.8 GW in BIOS. The costs of interconnectors as well as additional enforcements in the electricity distribution grid are not included in the STREAM modeling framework, which means that total system costs in EVS should be increased accordingly.

In BIOS, fuel costs are the key factor rendering the scenario the most expensive. Given the high utilization of biofuels in the transportation sector, BIOS uses €1.75 billion more as fuel input costs for fuel refinery processes compared to CNS. The capital cost expenditures are, however, lower compared to CNS given that the lower capital costs in the power and heating sector are about €0.6 billion.

Finally, fossil fuels are, to a limited extent, used in the transportation sector in CNS. Thus, compared to CNS, costs related to CO_2 emission reduce in both BIOS and EVS.

4.5. Sensitivities of main assumptions

A sensitivity analysis is conducted to clarify the robustness of the model results. The effects on the total annual system cost are assessed by separately varying the four assumption parameters, that is, cost (investment and maintenance) of EVs and methanol cars, bioenergy prices, and CO_2 price.

STREAM is a scenario simulation tool where scenarios are exogenously specified. Thus, changes in input prices, for example, fuel and CO_2 prices as well as CAPEX and OPEX, will not affect the generation portfolio in the energy sectors, but will affect the total system costs. Because of this modeling approach, linear relationships between input prices and total annual system cost become apparent. Figure 10 illustrates the sensitivity results.

The results show that total annual system cost in all three scenarios is sensitive to changes in bioenergy prices. Changes in costs (investment and maintenance) of car types have varying effects on the scenarios. BIOS is sensitive to changes in the costs of methanol cars, while EVS is sensitive to changes in costs of EVs. In addition, cost reductions or costs higher than estimated in the car industry presumably follow those in other transportations segments, for example, cargo vans, and buses. Finally, the model results in all scenarios seem to be robust to changes in CO_2 prices because the future energy system in all scenarios is almost carbon neutral.

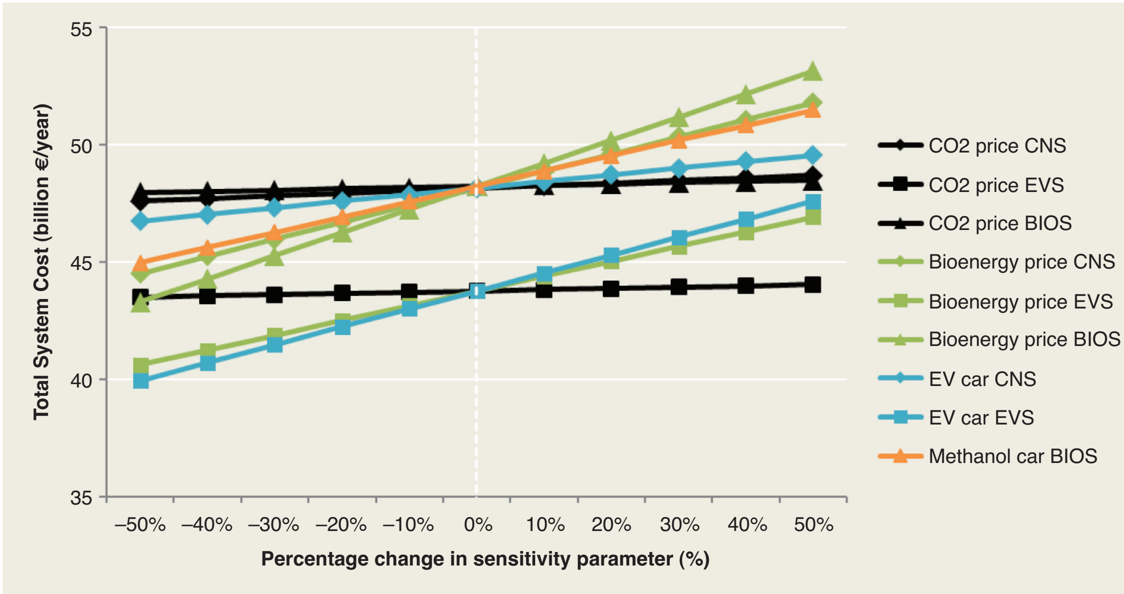

Figure 10: Sensitivity analysis for three 2050 scenario (changes in total annual system cost (y axis) caused by those in the main assumption parameters, i.e., cost (investment and maintenance) of EVs and methanol cars, bioenergy prices, and CO_2 price (x axis)).

The main model results highlight that EVS yields the least expensive solution. Furthermore, the sensitivity analysis shows that even when varying the sensitivity parameters ±50%, EVS remains the most cost-efficient scenario in all cases. STREAM computes the socioeconomic value of the energy system. To achieve a pathway such as that in EVS, the scenario should be feasible from both a socio- and private-economic perspective. If, however, the private consumer is not directed toward investments in EVs, policy instruments such as support schemes are necessary to promote such pathways.

Comparing EVS with CNS, the sensitivity analysis results shows that 50% higher costs of EVs makes CNS 4% more expensive than EVS. While 50% lower costs of EVs leads to a scenario where EVS is 14.6% cheaper than CNS.

The model simulations showed that BIOS is 0.2% more expensive compared to CNS. However, analyzing a situation in which the cost of methanol cars are reduced by 10%, the total annual system cost in BIOS is 1.2% lower than CNS. Bioenergy resources are widely used in all future scenarios; however, BIOS consumes more bioenergy resources and thus, is more sensitive to price changes. Reducing prices of bioenergy resources by 10% leads to costs reductions in both BIOS and CNS, although BIOS becomes 0.4% more cost-efficient than CNS.

Comparing EVS and BIOS, the costs of different car types are the most sensitive parameters and can lead to a shift in the best performing scenario, that is, from EVS to BIOS. If the cost of EVs are 60% higher than the estimated cost by 2050, the total annual system cost of BIOS is 0.3% lower compared to that of EVS.

4.5.1. Sensitivity scenarios

In addition to the sensitivity analysis, sensitivity scenarios are conducted to clarify the impact of significant scenario parameters. Three sensitivity scenarios are hence developed:

1. EVS-Night (night charging of EVs – less flexible compared to the predefined settings in EVS)
2. BIOS-Biodiesel (biodiesel is used instead of methanol in BIOS)
3. Electrofuel (electrofuel is used instead of methanol in BIOS and EVS)

EVS-Night-scenario:

The EVS-Night-scenario is developed to investigate the impact of limiting demand-side management in terms of charging EVs is a flexible manner. In this scenario, all EVs are assumed to be charged during nighttime. Today, since classic electricity demand is lower during night hours, this charging decision can be assumed as flexible to a certain extent. However, as EVs charging does not consider residual load, this scenario is less flexible compared to the settings in EVS. The scenario results for the STREAM simulation show that the total annual system costs in the EVS-Night-scenario are 0.8% higher than that in EVS. Furthermore, the necessary power transmission capacity increases in EVS-Night-scenario to 22.2 GW, which is 10% higher than that in EVS. Since the costs of installing transmission capacity are not included in STREAM, these costs will further increase total annual system costs. These results complement existing findings [18–22] and indicate the potential benefit of applying demand-side management in energy systems with high VRE penetration. To investigate the full value of flexibility in power systems, more sophisticated modeling tools are needed [22].

BIOS-Biodiesel-scenario:
In BIOS, methanol is the preferred fuel used in transportation, while CNS uses biodiesel. A sensitivity scenario, BIOS-Biodiesel, is assumed to elucidate the impact of relying on biodiesel instead of methanol in BIOS. BIOS-Biodiesel obtains a total annual system cost that is 1.3% higher than that in BIOS. A potential benefit of using biodiesel is that 4% fewer bioenergy resources are used. The scenario results show that shifting between methanol and biodiesel do not cause significant changes.

Electrofuel-scenarios:
Electrofuels are produced by combining a carbon source from, for example, biomass with hydrogen from electrolyzes, and has, in this study, properties of methanol or DME. Electrofuels based on biomass hydrogenation is an effective way to produce more fuel using the same available biomass resource. Moreover, the production of electrofuels increases the integration of the power, gas, heating, and transportation system. In the electrofuel scenarios, methanol- or DME-based transportation shifts to one using electrofuels. The results from the sensitivity scenarios show that less biomass is used in the transportation sector. In Electrofuel-BIOS, the bioenergy utilization in the transportation sector reduces by 48% from 577 PJ to 298 PJ, while bioenergy use in Electrofuel-EVS is 138 PJ, which is 29% lower. As biomass utilization in the Electrofuel-scenarios decreases, electricity demand increases: it increases by 18% in Electrofuel-BIOS and by 4% in Electrofuel-EVS, indicating similar demand levels in both scenarios. This evidently influences the required transmission capacity, which for both scenarios is 22.5 GW, and thus, an increase of 11% for Electrofuel-EVS compared to that for EVS. However, hydrogen can be produced by flexibly operating electrolyzes, and as a result, could increase flexibility in the power system.

5. Conclusions

This study investigated the long-term role of electricity or biofuels in decarbonizing the Swedish transportation sector by 2050. By adopting a holistic energy system perspective, it provided an in-depth discussion of the transportation sector while accounting for future interrelations between the power and heating sectors. The energy system model, STREAM, computed the socioeconomic system cost and simulated the system integration of the transportation sector with the electricity and heating sectors on the basis of an hourly resolution.

A configuration of supply mix in the power, heat, residential, tertiary, and industrial sector was adopted from a known scenario (CNS) outlined in the Nordic Energy Technology Perspective 2013. In this context, the study compared CNS with two transportation scenarios: high percentage of electric vehicles (EVS) or high percentage of biofuel use (BIOS) in the transportation sector.

The result showed that a Swedish transportation sector with a high share of EVs by 2050 could lead to the most cost-effective solution under the given assumptions and reduce the total annual system cost by 9.1% compared to CNS. The transportation configuration in BIOS achieved the highest total annual system cost, which was 0.2% higher than that in CNS. In this study, bioenergy resources played a prominent role in the future transportation system, accounting for 57%, 62%, and 99% of total transportation final energy use in EVS, CNS, and BIOS, respectively.

Despite the considerable bioenergy resources appear in Sweden, the use of bioenergy resources exceeds that of available domestic resources in all scenarios. Further, this study discussed the high utilization of bioenergy resources in the power and heating sector. The results showed that the Swedish transportation sector accounted for 57%, 35%, and 104% of the national biomass resources in CNS, EVS, and BIOS, respectively. The market price of bioenergy resources depends on global utilization. Then, the robustness of the scenario results was tested by changing bioenergy prices in a sensitivity analysis. Each scenario was highly sensitive to changes in bioenergy prices; moreover, the results did not offer different best-performing solutions even in the case of same bioenergy prices in all scenarios.

EVs and methanol cars are key technologies in the two transportation scenarios. The scenario results demonstrated sensitivity to changes in the costs (investment and maintenance) of different vehicle types. Thus, the future development of these two vehicle technologies seems important.

Three additional sensitivity scenarios were assumed to identify the impact of charging all EVs during night hours, using biodiesel instead of methanol or DME in BIOS, and using electrofuels instead of methanol or DME in EVS and BIOS. The findings indicated the potential benefit of applying flexible charging of EVs, and that the differences in utilization of either methanol/DME or biodiesel are not significant. Moreover, the findings presented the potential benefits of the effective utilization of finite biomass resources and system integration using biomass hydrogenation to produce fuels for transportation.

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